The Future Global Earth Observing System:
System Requirements and Architecture

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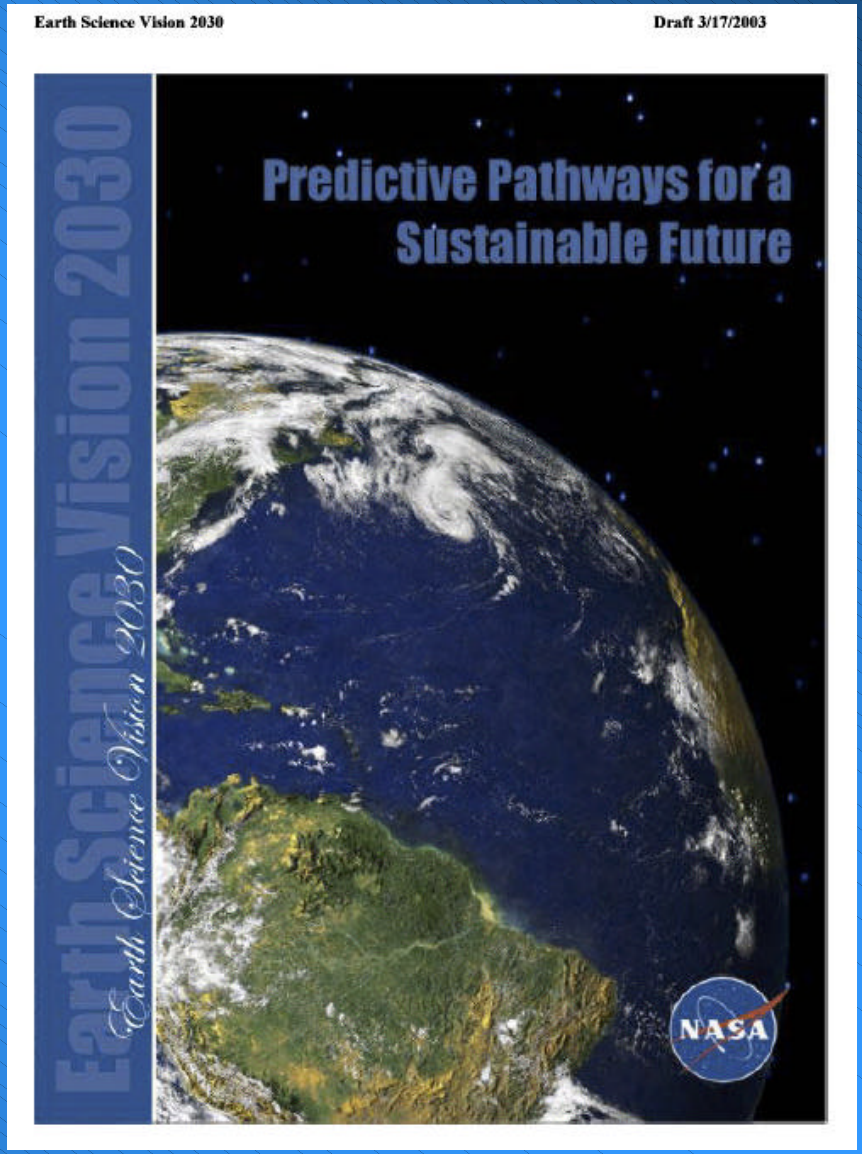
Future Global Earth Observing System

Develop the outlook for the far-future Earth observing system:

- provide a *long-term vision*
- suggest major new *observational goals* required for prediction of full Earth system processes
- *evaluate feasibility* of a full global Earth observing system
- identify *technical hurdles*



Future Global Earth Observing System: *Motivation*

The variability of Earth's environment links to life through:

the availability of water, production of food, effects of atmospheric composition, ecosystem and human health, and human impacts and migration.

As the human population grows, the links between the Earth environment and human needs and impacts also grow:

the needs for quantitative prediction of the Earth system therefore increase.

We must move beyond basic understandings of the Earth to a quantitative predictive capability for future changes of Earth's:

atmosphere, oceans, biosphere and solid Earth.

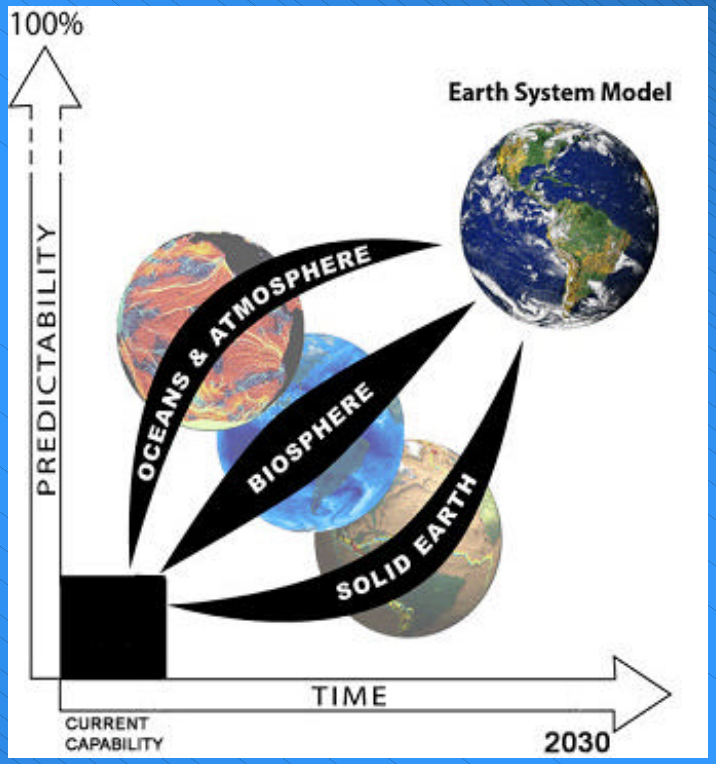
These predictions will enable informed societal decisions that will enhance the quality of life, economic sustainability, and global social stability.

Future Global Earth Observing System:
Linking Observations & Models

The future Earth observation system will require a paradigm shift:

- **complete observation of the full Earth system**
  - **an international suite of Earth observation systems**
  - **all observations made at the appropriate:**
    - **precision and accuracy, and**
    - **spatial & temporal resolution**

    for the processes being observed.
- **observations assimilated into a family of interacting models including**
  - **all major Earth system components:**
    - **atmosphere & oceans**
    - **biosphere**
    - **solid Earth**
  - **and linkages between components**



Future Global Earth Observing System: *Design Study*

We considered six Earth sciences topics:

- ***The genesis and development of extreme weather***
- ***Seasonal climate change and predictability***
- ***Sea level change***
- ***Earthquake prediction***
- ***Availability of water***
- ***Biosphere - climate interactions and human interactions***

Additional important topics are easily added.

Future Global Earth Observing System:

Topic 1: Genesis and Development of Extreme Weather

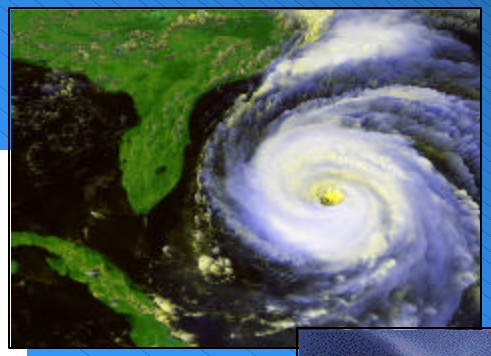


Table 2.2. Weather Forecasting Goals

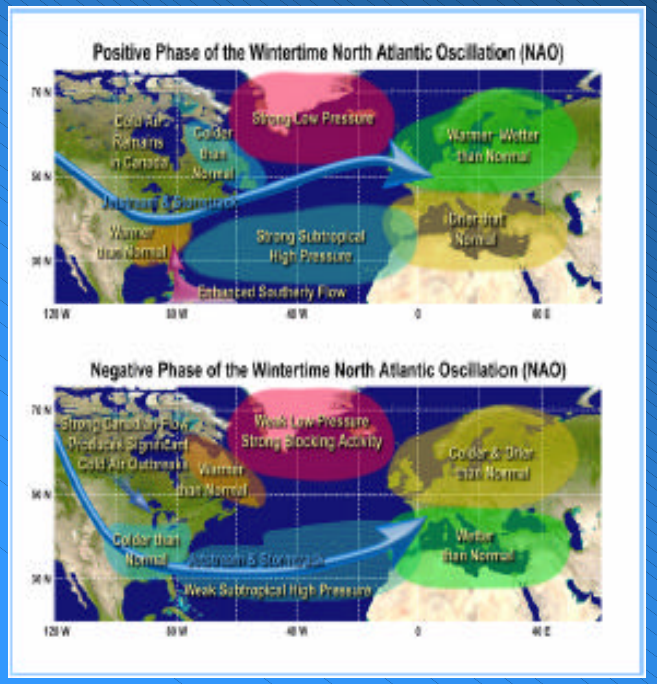
Phenomenon (Today's Capability)	Goals for 2010	Vision for 2025
3-day forecast at 93%	5-day forecast at > 90%	7-10-day forecast at > 90%
3-day rainfall forecast not achievable	3-day rainfall forecast routine	7-day rainfall forecast routine
Winter storms (13 hours advance)	Winter storms forecast 1 day in advance; probabilistic guidance to 5 days	Winter storm forecasts >3 days, with probabilistic guidance to 10 days
3-day severe local storm forecast with low-moderate confidence	5-day severe local storm forecasts with moderate confidence	7-day probabilistic severe local storm forecasts, with moderate to high confidence
Thunderstorm occurrence (convective initiation) to 16 min	Thunderstorm occurrence to 30 min	Thunderstorm occurrence >2-3 hrs
Tornado lead time 10 min	Tornado lead time 20 min	Tornado lead time 30 min
Flash floods 47 min	Flash floods 1 hour	Flash floods >2-3 hours
Hurricane landfall (125 nautical miles (nm) at 2 days)	Hurricane landfall 100 nm at 2 days	Hurricane landfall 75 nm at 3 days
Hurricane intensity (16 knots)	Hurricane intensity 12 knots	Hurricane intensity 9 knots
Air quality day by day	Air quality at 2 days	Air quality at 7-10 days

Extreme Weather Measurements	Frequency	Horizontal Resolution	Precision/ accuracy
Tropospheric wind profiles (20 levels in troposphere)	3 Hours	5 km	1 m/s per horizontal component
Wind vectors within storm systems (20 levels in troposphere)	1-3 Hours	5-25 km	3 m/s per horizontal component
Temperature and water vapor profiles in clear air (20 levels in troposphere)	1-3 hours	5 km	1° C, T & Td
Temperature and water vapor profiles within storm systems (20 levels in troposphere)	1-3 Hours	5-25 km	1° C, T & Td
Surface precipitation	Hourly	5-25 km	5-10 mm/h
3-D precipitation structure (20 levels in troposphere)	3 Hours	5-25 km	5-10 mm/h
Ocean mixed layer depth	Weekly	10 km	10%

Future Global Earth Observing System:

Topic 2: Seasonal Climate Change and Predictability

Today	2015	2030
Week to month short-term climate predictions exceed present capabilities.	Initial success in forecasting short-term climate.	Short-term climate predictions routine with 90% success over week to month time periods.
First steps taken linking weather and climate to forecasts of flooding, crop and disease.	Short-term climate predictions link to forecasts of adverse weather, flooding, crop, disease outbreaks.	Short term climate predictions are sufficiently accurate that societal actions can be taken.
First steps taken toward understanding of causative factors for el Nino occurrence.	Past el Nino occurrences can be reproduced, and experimental forecasts are routine.	15-20 month El Nino prediction
Predictions of annual rainfall on regional scales are based on climatology and persistence.	Useful predictions of annual rainfall on regional scales based on climate predictions.	Routine global forecasts of annual rainfall on regional scales accurate enough for t the needs of agriculture.
First steps taken toward understanding of short-term climate variability	Causative factors for short-term climate variations understood.	10-year climate forecasts



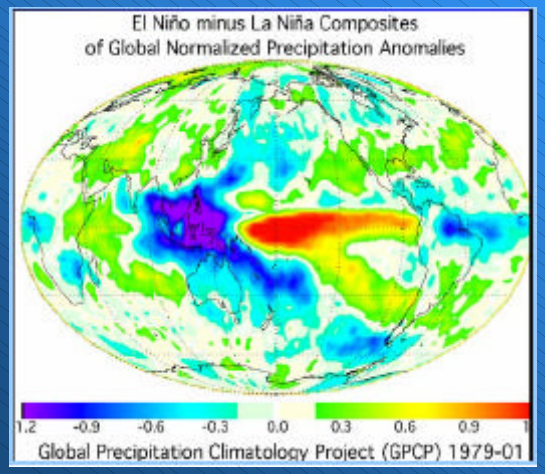


Table 2.1. Key Climate Measurement Goals

Measurement Climate Measurements	Frequency	Horizontal Resolution	Precision/ accuracy
Ocean evaporation rate	Daily	10 km	5%
Ocean mixed layer depth	Weekly	10 km	10%
Sea Ice thickness	Monthly	5km	5cm
Soil Moisture	Daily	< 1 km	10%
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly To Weekly	< 1 km	NA
Stream flow	Daily	NA	10%
Aerosol distribution and absorption properties	Hourly	< 1 km	10%
Atmospheric ozone	Hourly	1km (vertical)	5%
Carbon dioxide and methane	Hourly	1km (horizontal)	1% (column)
Atmospheric gases	Hourly	1km (H & V)	1-10%

Future Global Earth Observing System:

Topic 3: Sea Level Change

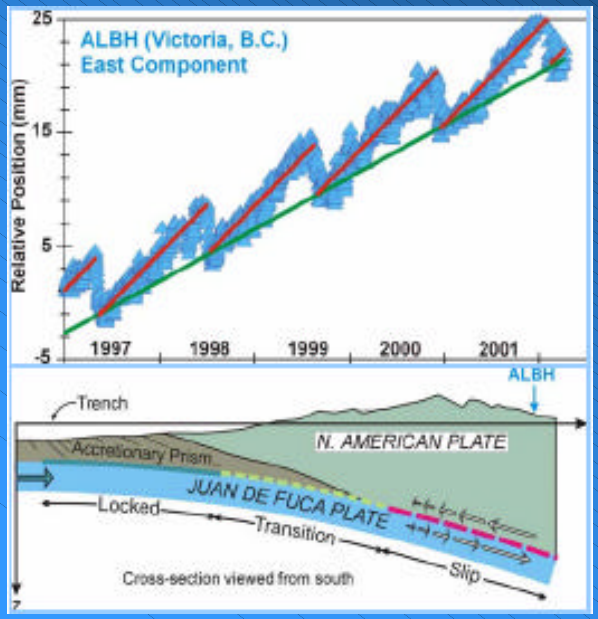
Today	2015	2030
Sea-level Change		
Large uncertainties in several significant potential contributors to sea level rise (ice sheets, coastal change)	Ice sheet state, evolution and dynamics understood	Accurate 10-yr and longer regional sea level prediction, including impacts on coastal erosion, coastal ecosystems and fresh water availability
Rudimentary knowledge of short-term ocean volume changes	Well-understood oceanic expansion term tied to short-term climate prediction models	
Regional variability poorly understood	Variable coastal response to sea level change understood	
Rudimentary knowledge of adaptability of coastal ecosystems to rising sea level	Impact of sea level change on coastal region habitability coming into focus	

Sea Level Measurements	Frequency	Horizontal Resolution	Precision/ accuracy
Ocean/Ice Mass Redistributions (gravity change)	Monthly	100s-1000s km (scale of drainage basin)	0.1 mm/yr sea level rise equivalent
Bathymetry	Once	5 km	10%
Ocean mixed layer depth	Weekly	10 km	10%
Coastal zone topography	Monthly	2-5 m pixels	<10 cm (height)
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams – ice sheet)	1 cm (height)
Ice motion (dynamics)	Monthly	100 m	1 m/yr (rate)
Ice Sheet and Bed Characteristics	10 Years	10 – 100 km	Bed topography to <10 m
Crustal Deformation (uplift/subsidence)	Daily To Weekly	10 m	1 cm (range) 0.5 mm/yr (rate) on annual basis
Soil Moisture	Daily	< 1 km	10%
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent
Reservoir and Aquifer Impoundment	Monthly	Scale of storage basin	0.1 mm/yr sea level rise equivalent

Future Global Earth Observing System:

Topic 4: Earthquake Prediction

Today	2015	2030
30-yr probabilistic earthquake assessments.	Experimental 5-yr earthquake forecasts.	Monthly earthquake hazard assessments at scale of major fault systems.
Earthquake physics poorly understood	Models of earthquake physics yielding reasonable success in representing observed fault system interactions.	Time-dependent models of crustal deformation due to tectonic loading and hydrology.
Knowledge of space-time spectrum of crustal deformation expanding	Aseismic and transient strain budget coming into focus	Full-spectrum of deformation understood
Daily to weekly volcanic activity warnings	Global inventory and warnings of active volcanoes	30-60 day volcanic eruption warnings
Magma dynamics models in development.	Evaluation and validation of magma dynamics models to predict eruptions	Impact of potential eruptions on atmospheric composition factored into climate models

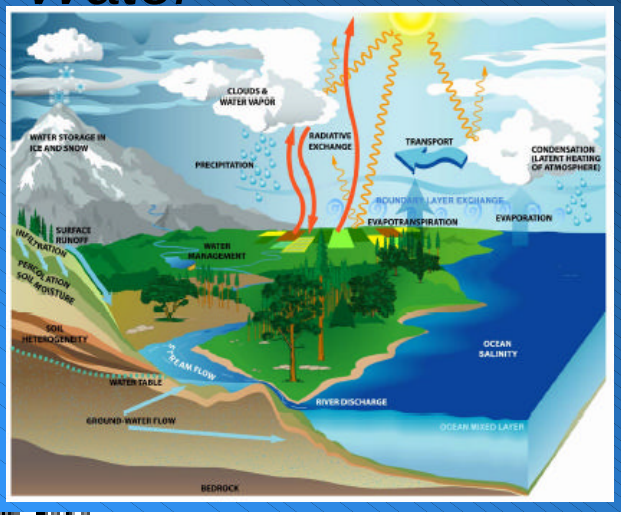


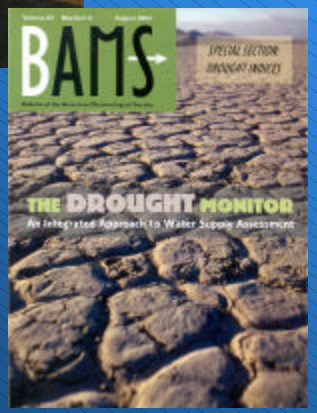
Measurements	Frequency	Horizontal Resolution	Precision/ accuracy
Crustal Deformation	Daily To Weekly	1-10 m	5 mm instantaneous, 1 mm/yr (rate over 10 yrs) accuracy
Crustal Mass Redistributions (gravity change)	Weekly	50-100 km	0.1 milligal accuracy
Subsurface sounding	Weekly	100 m/ 10 m depth	5% saturation

Future Global Earth Observing System:

Topic 5: Availability of Water

Today	2015	2030
Understanding of the role of clouds and precipitation in weather and climate.	Credible progress towards representation and forecasting of clouds in weather and climate models.	Routine predictions of clouds and precipitation in weather and climate models.
Prediction of land surface state—snow, soil moisture, surface water, ET—at a micro level.	Land surface state can be reliably predicted independently of the weather and climate variability.	Land surface influence on the climate and biosphere systems can be predicted.
Components of the water cycle understood, but water budget not accurately closed.	Capability for prediction of water cycle trends on regional and global scales.	Can routinely predict water cycle variability and extreme events on regional and global scales.





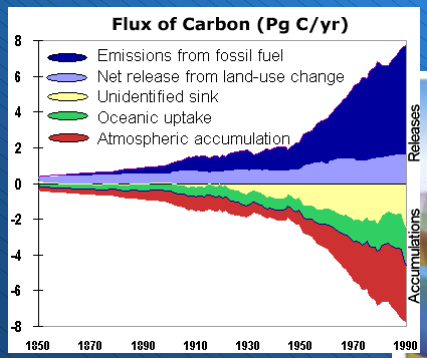
Measurements	Frequency	Spatial Resolution	Precision
Soil Moisture	Daily	< 1 km	10%
Precipitation	Hourly	5-25 km	5-10 mm/h
Stream flow	Daily	NA	10%
Sea Ice thickness	Monthly	5km	5cm
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly to Weekly	< 1 km	NA
Ocean evaporation rate	Daily	10 km	5%
Reservoir and Aquifer Impoundment	Monthly	Scale of storage basin	0.1 mm/yr sea level rise equivalent
Ice sheet elevation	Weekly	< 1 km	1%
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams – ice sheet)	1 cm (height)

22 July 2003

Future Global Earth Observing System:

Topic 6: Biosphere, Climate and Human Interactions

Biosphere-climate Interactions		
Today	**2015**	**2030**
Observations allow relating net primary production with carbon balance.	Carbon sources and sinks for North America are quantified well enough to allow carbon management decisions.	Prediction of global, high resolution, monthly carbon exchange by oceans, coastal zone, and terrestrial biosphere
Accurate characterization of annual biogeochemical cycling and biospheric processes in ocean and terrestrial models based on remote sensing data.	Understand the effects of land use recovery on carbon balance, including explicit understanding of biomass, soils, and coastal zone	Capability to understand and predict the natural regulatory controls on biosphere processes.
Teleconnections between climate variability and ecosystem response understood on a statistical basis.	Capability to forecast ecosystem response to climate and weather variability on interannual and longer time scales.	Capacity to forecast ecosystem response to human influences on biosphere-atmosphere exchanges.
Capability for coarse resolution, global net primary production modeling.	Capability for ecosystem-specific, carbon management modeling and forecasting.	Capability to model fine space and time scales of biosphere response to climate variation (adequate for public applications)



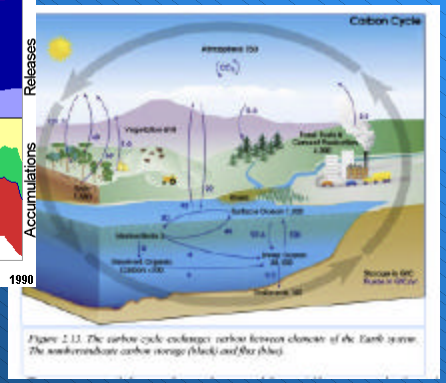


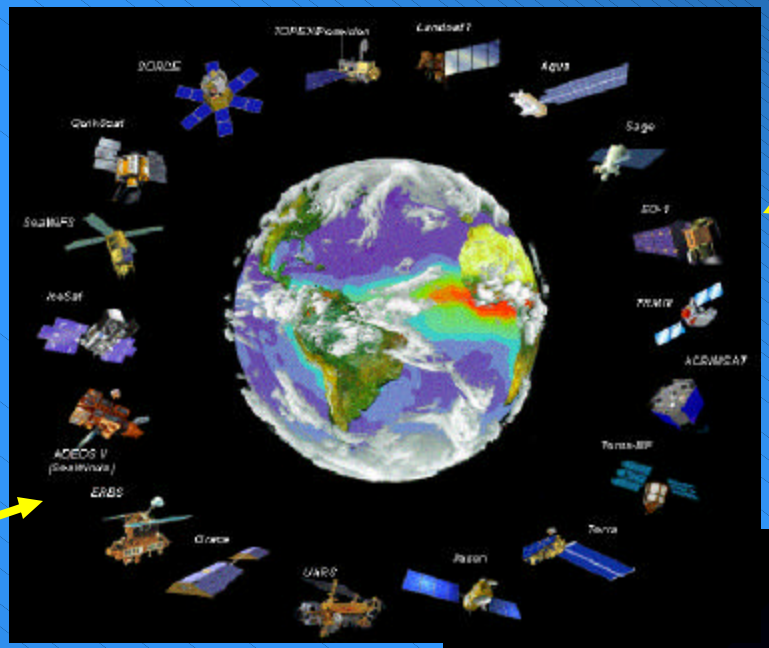
Table 2.7. Measurement Goals for the Biosphere on Land and Sea

Biosphere Measurements	**Frequency**	**Horizontal Resolution**	**Precision/ accuracy**
Mixed layer depth, coastal zone	Weekly	10-100 m	10%
Ocean Nutrient fields (N, Si, Fe), aerosol deposition, functional groups	Weekly	10 km	30 %
Ocean Colored dissolved organic matter Chlorophyll and other pigments Functional groups Bathymetry and bottom reflectance Nutrient concentration (N, Si, Fe, P)	Daily-Weekly	100 m	10%
Ocean Physiological state (fluorescence)	Daily	100 m	20%
Bathymetry	Daily-Weekly	100 m	10%
Phenological state (leaf out, senescence)	Diurnally	1 km	Less than one day
Biochemical composition of plant canopies (N, lignin, pigments, chlorophylls, etc.) Responses to multiple stressors (long-term)	Weekly	100-200 m	25%
Fire properties (energy release rates, rate of spread, gas/aerosol loading, soil heating)	Daily	100 m	20%
Standing biomass over time	Monthly-Annual	100 m	10%
Vegetation structure, successional state, primary & secondary vegetation condition	Monthly	100 m	20%
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly To Weekly	< 1 km	NA
Aerosol distribution and absorption properties	Hourly	< 1 km	10%
Atmospheric ozone	Hourly	1km (vertical)	5%
Carbon dioxide and methane	Hourly	1km (horizontal)	1% (column)
Atmospheric gases	Hourly	1km (H & V)	1-10%

Future Global Earth Observing System:

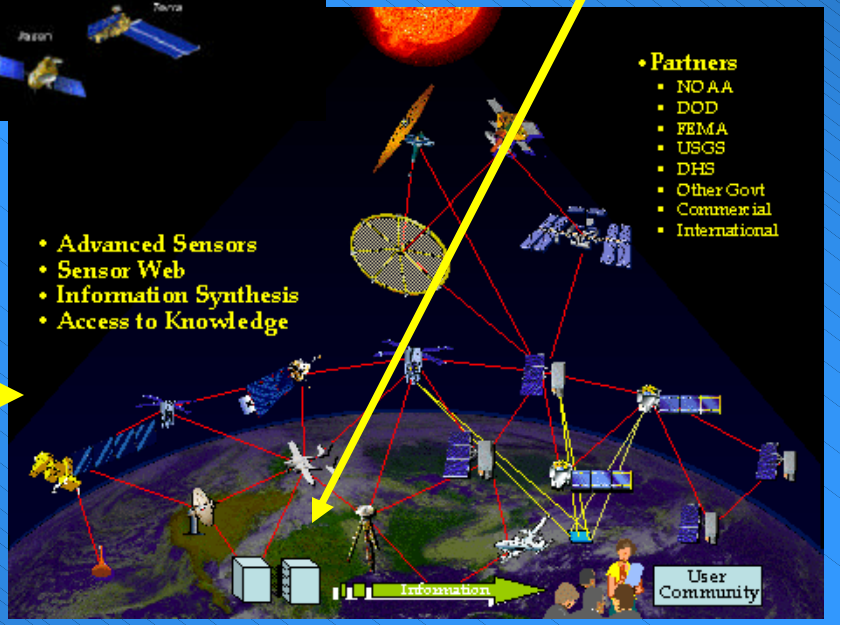
How realistic is this future vision?

- Current Earth observing satellites:
  - GEO + LEO operational satellites from US & other nations
  - a multitude of research satellites



How many satellites & what do they measure?

How are data accessed?



- Sensor Web
  - –links data to computational nodes
  - –synthesizes information for applications

Future Global Earth Observing System:

Review the Observation Goals

Orbits for each measurement can be selected based on the requirements for:

- frequency of observation
- spatial sampling
- observational technologies

Temporal and spatial sampling requirements are set by the characteristic scales of the phenomena

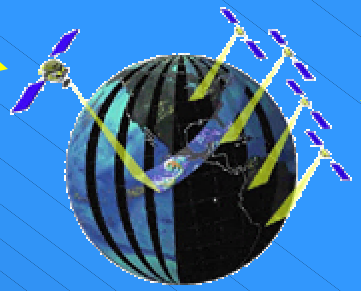
Measurement	Frequency	Horizontal Resolution	Precision/accuracy	Predictive Goal
Ocean evaporation rate	Daily	10 km	5%	C, W
Ocean mixed layer depth	Weekly	10 km	10%	C, EW, S
Ocean mixed layer depth, coastal zone	Weekly	10-100 m	10%	B
Ocean/Ice Mass Redistributions (gravity change)	Monthly	100s-1000s km (drainage basin)	0.1 mm/yr sea level rise equivalent	S
Aerosol distribution and absorption properties	Hourly	< 1 km	10%	C, B
Atmospheric ozone	Hourly	1km (V)	5%	C, B
Carbon dioxide and methane	Hourly	1km (H)	1% (column)	C, B
Atmospheric gases	Hourly	1km(H&V)	1-10%	C, B
Tropospheric wind profiles (20 levels)	3 Hours	5 km	1 m/s	E
Wind vectors within storm systems (20 levels)	1-3 Hours	5-25 km	3 m/s	E
Temperature and water vapor profiles in clear air (20 levels)	1-3 hours	5 km	1° C, T & Td	E
Temperature and water vapor profiles within storms (20 levels)	1-3 Hours	5-25 km	1° C, T & Td	E
[illegible]	Hourly	5-25 km	5-10 mm/h	E, W
3-D precipitation structure (20 levels in troposphere)	3 Hours	5-25 km	5-10 mm/h	E
Sea Ice thickness	Monthly	5km	5cm	C, W
Soil Moisture	Daily	< 1 km	10%	C, S, W
Soil properties (carbon stocks, nutrient availability, hydrologic properties)	Monthly - Weekly	< 1 km	NA	C, W, B
Stream [illegible]	Daily	NA	10%	C, W
Bathymetry	Daily- Weekly	100 m	10%	B
Coastal zone topography	Monthly	2-5 m pixels	<10 cm	S
Ice Sheet Topographic Change	< 1 Year	1-10 km (ice streams & sheets)	1 cm (height)	S, W
Ice sheet elevation	Weekly	< 1 km	1%	W
Ice motion (dynamics)	Monthly	100 m	1 m/yr (rate)	S
Ice Sheet and Bed Characteristics	Yearly	10 – 100 km	Bed topography to <10 m	S
Crustal Deformation (uplift/subsidence)	Daily To Weekly	10 m	1 cm (range); 0.5 mm/yr (rate) on annual basis	S, E
Crustal Mass Redistributions (gravity change)	Weekly	50-100 km	0.1 milligal accuracy	E
Soil moisture sounding	Weekly	100 m/ 10 m depth	5% saturation	E
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent	S, W
Reservoir and Aquifer Impoundment	[illegible]	Scale of storage basin	0.1 mm/yr sea level rise equivalent	S, W
Ocean Nutrient fields (N, Si, Fe), aerosol deposition, functional groups	Weekly	10 km	30 %	B
Ocean Colored dissolved organic matter, Chlorophyll and other pigments, Functional groups, Bathymetry and bottom reflectance, Nutrient concentration (N, Si, Fe, P)	Daily- Weekly	100 m	10%	B
Ocean Physiological state (fluorescence)	Daily	100 m	20%	B
Phenological state (leaf out, senescence)	Diurnally	1 km	Less than one day	B
Biochemical composition of plant canopies (N, lignin, pigments, chlorophylls, etc.) Responses to multiple stressors (long-term)	Weekly	100-200 m	25%	B
Fire properties (energy release rates, rate of spread, gas/aerosol loading, soil heating)	Daily	100 m	20%	B
Standing biomass over time	Monthly- Annual	100 m	10%	B

Predictive goal categories:

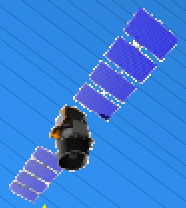
- Climate
- Extreme Weather
- Sea Level
- Earthquake
- Water
- Biosphere

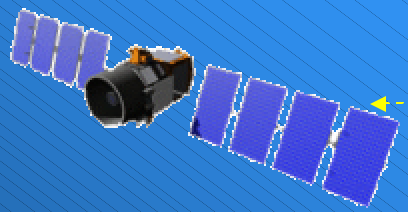
Future Global Earth Observing System:
Orbits, Constellations, & Instruments

Special LEO:
- **4-6 satellites**
- **3 weekly scales**
- **longer wavelength instruments**



LEO orbits:
8-10 satellites provide:
- **multi-hour « multi-day scales**
- **longer wavelength instruments**





Geostationary Orbits:
6-8 satellites provide:
- **hourly « diurnal scales**
- **short wavelength instruments**

Future Global Earth Observing System:
Review the Observation Goals

Measurement	Frequency	Horizontal Resolution	Precision/accuracy	Predictive Goal
Ocean evaporation rate	Daily	10 km	5%	C, W
Ocean mixed layer depth	Weekly	10 km	10%	C, EW, S
Ocean mixed layer depth, coastal zone	Weekly	10-100 m	10%	B
Ocean/Ice Mass Redistributions (gravity change)	Monthly	100s-1000s km (drainage basin)	0.1 mm/yr sea level rise equivalent	S
Aerosol di…			10%	C, B
At…				C, B
			…m)	C, B
				C, B
				E
				E
			…Td	E
			…, T & Td	E
Surface p…			5-10 mm/h	E, W
3-D precipitation str…			5-10 mm/h	E
Sea Ice thickness	Monthly	5km	5cm	C, W
Soil Moisture	Daily	< 1 km	10%	C, S, W
Soil properties (carbon stocks, nutrient availability, hy… properties)	Monthly - Weekly	< 1 km	NA	C, W, B
Stream flow	Daily	NA	10%	C, W
Bathymetry	Daily-Weekly	100 m	10%	B
Coastal zone topography	Monthly	2-5 m pixels	<10 cm	S
Ice Sheet Topo… Change	< 1 Year	1-10 km (ice streams & sheets)	1 cm (height)	S, W
I… sheet elevation	Weekly	< 1 km	1%	W
Ice motion (dynamics)	Monthly	100 m	1 m/yr (rate)	S
Ice Sheet and Bed Characteristics	Yearly	10 – 100 km	Bed topography to <10 m	S
Crustal Deformation (uplift/subsidence)	Daily To Weekly	10 m	1 cm (range); 0.5 mm/yr (rate) on annual basis	S, E
Crustal Mass Redistributions (gravity change)	Weekly	50-100 km	0.1 milligal accuracy	E
Soil… isture sounding	Weekly	100 m/ 10 m depth	5% saturation	E
Snow Pack	Weekly	< 1 km	0.1 mm/yr sea level rise equivalent	S, W
Reservoir and Aquifer Impoundment	…	Scale of storage basin	0.1 mm/yr sea level rise equivalent	S, W
Ocean Nutrient fields (N, Si, Fe), aerosol deposition, functional groups	Weekly	10 km	30 %	B
Ocean Colored dissolved organic matter, Chlorophyll and other pigments, Functional groups, Bathymetry and bottom reflectance, Nutrient concentration (N, Si, Fe, P)	Daily-Weekly	100 m	10%	B
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Fire properties (energy release rates, rate of spread, gas/aerosol loading, soil heating)	Daily	100 m	20%	B
Standing biomass over time	Monthly-Annual	100 m	10%	B

Temporal and spatial sampling requirements are set by the characteristic scales of the phenomena

Future Global Earth Observing System

Communication, Computation & Delivery of Data

Data requirements for ~1 hourly, 0.1 km resolution with:

- 10 variables
- 10 measurements / variable
- 20 levels in atmosphere

~ 10^{12} baud

Ability of recipient to make a decision:

- either binary (yes/no)
- or between choices

Ability of recipient to ingest the data:

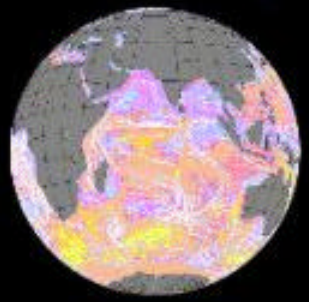
- for govt. function, industry, science, public

~ equivalent to present workstations or ~ 10^{6} baud

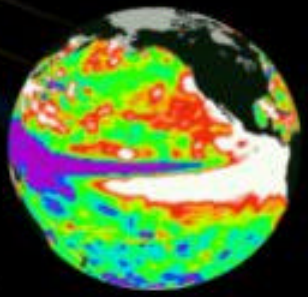
Systems of Planet Earth

How They Interact and Impact Life

Earth Radiation Environment
- Earth Magnetic Field
- Orbit Dynamics
- Solar Cycle / Events

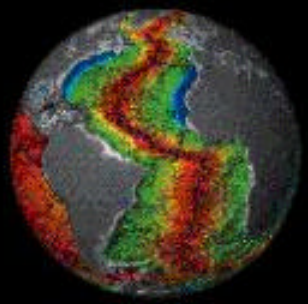


Atmosphere - Ocean Dynamics
- Ocean Heat Transport
- Seasonal Variability
- Storm Systems



Climate
- Aerosols
- Greenhouse Gasses
- Hydrological Cycle

Biosphere
- Availability of Water
- Ecosystem Health
- Quality of Life



Solid Earth
- Earthquakes
- Sea Level
- Volcanoes